2020 DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting

Cummins Electric Truck with Range-Extending Engine (ETREE)Project ID: ELT189

Project ID: ELT189

Principal Investigator:
Jesse Dalton
Cummins, Inc.

June 3, 2020

Project Overview

TIMELINE

- 4 year project
- Project start date: July 2016
- Project end date: August 2020
- Percent complete: 95%

BARRIERS

- EV-based commercial vehicle which meets needs of class 6-7 pickup & delivery fleets:
  - Complete the route regardless of environmental conditions with little to no performance degradation
  - Robust, cost-effective powertrain which emphasizes use of grid electricity

BUDGET

Project (overall):	$9,832,821
DOE Share:	$4,126,570
FFRDC:	$355,708
Contractor funding:	$5,466,251
Funding received (1/2020):	$4,116,570

PARTNERS

- Cummins
  - PACCAR
  - Argonne National Lab
  - National Renewable Energy Lab
  - The Ohio State University

Objectives

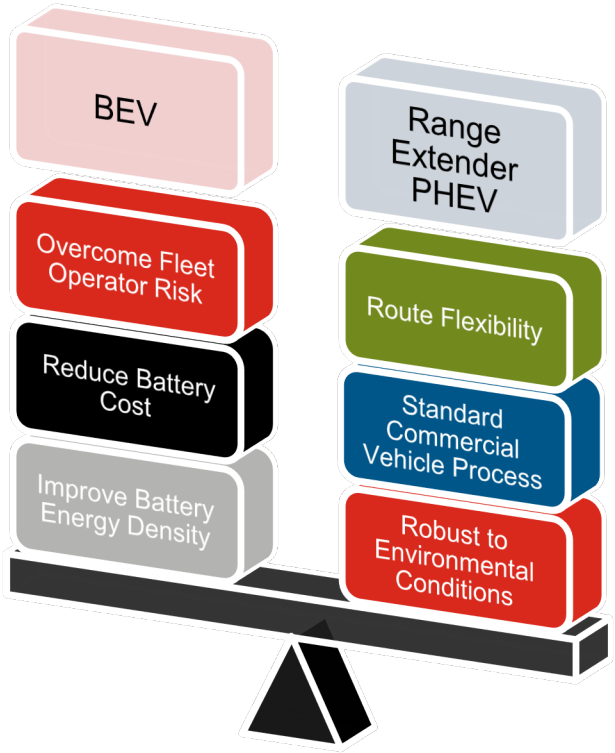
(1)

- Using electrification, improve the Kenworth K270 & Peterbilt Model 220 to substantially reduce (> 50%) fuel consumption for the **class 6 pickup & delivery market** while meeting requirements of the existing trucks
- Investigate the potential to improve a commercial EV using:
  - range extending engine / generator with optimized controls
- Develop hybrid system controls technology focused on battery state-of-charge trajectory management and vehicle integration (electrified accessories, thermal management) systems
- Demonstrate architecture capability on road and in fleet use

1. Courtesy of PACCAR Inc

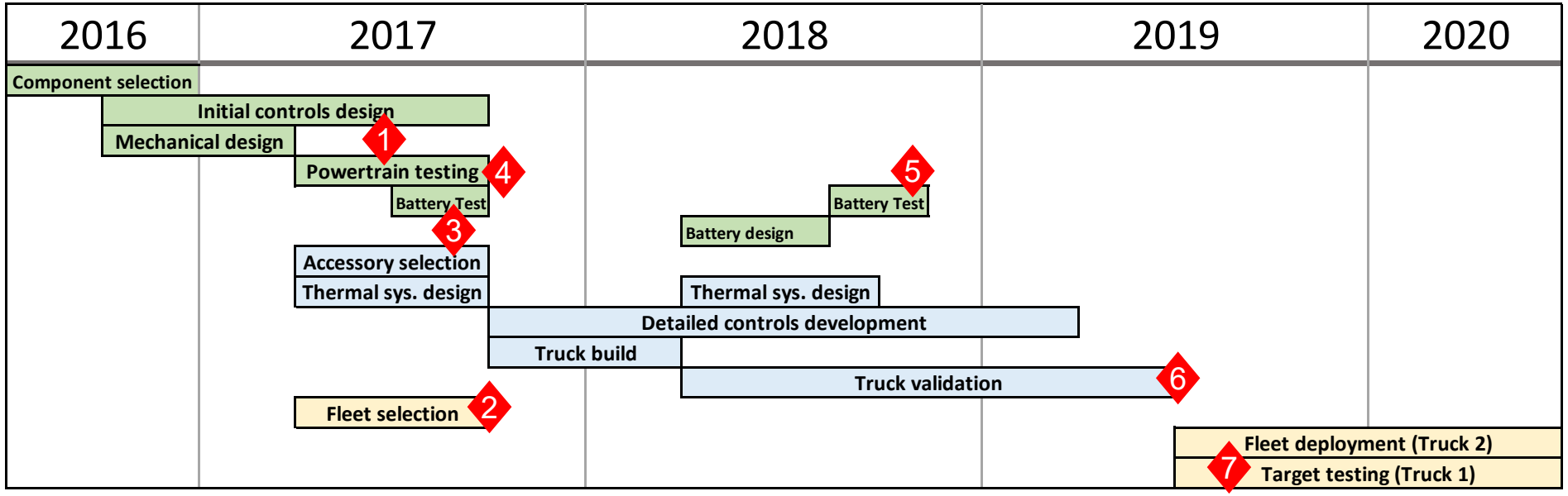
Relevance of ETREE project

- Two keys to widespread electrified commercial vehicle adoption
  1. For pure EV, battery improvements are needed: cost(↓) & energy density(↑)
  2. Must overcome fleet operator risks such as: operations in cold climates & hilly terrain, or where majority of conventional trucks are replaced with EV
- In the near- to medium-term, solved by: a PHEV w/ low-cost range extender (REx) to provide route flexibility
  - Proven to work over wide variety of missions & environmental conditions
  - Manufactured, serviced, certified, delivered, integrated using standard commercial vehicle processes
- Vehicle developed in this project can be considered a prototype for a commercially viable heavily electrified commercial vehicle
- ETREE will deliver equivalent continuous performance (transmission output torque and power) and range as conventional class 6 truck



EV – electric vehicle PHEV – plug-in electric vehicle REx – Range Extender

Milestones & Plan



	Milestone	Budget Period	Scheduled Completion	Actual
1	Fuel consumption reduction objectives met in test cell (go / no-go)	1	6/30/2017	6/6/2017
2	Fleet demo partner selected	1	6/30/2017	8/27/2017
3	Battery tested in lab	2	7/31/2017	8/7/2017
4	Powertrain testing in test cell complete	2	10/15/2017	9/22/2017
5	Truck 1 operational with updated batteries	2	10/30/2018	12/15/2018
6	SAE J1526 testing complete & fuel consumption goals met (go / no-go)	2	6/30/2018	8/15/2019
7	Release truck to first fleet operator	3	7/15/2018	1/15/19

Approach

Selection of Fleet Demo Partner

- **Frito-Lay** selected as primary ETREE demo partner
  - Operates fixed defined routes, 15-100+ mi/day, delivering chips/snack food
  - ETREE Peterbilt Model 220 will operate on (typically) 50-80 mi/day routes from the Indianapolis distribution center
- PepsiCo / Frito-Lay is a significant proponent and adopter of alternative fueled, including electrified, vehicles, and one of the largest operators of class 6-7 trucks

"The Range Extended capability of the ETREE vehicle is of great interest to PepsiCo. It provides real world opportunity for zero emission driving and also the ability to drive extended miles when needed, with no interruption"
- Mike O'Connell (VP Fleet, Supply Chain and Sustainability) PepsiCo

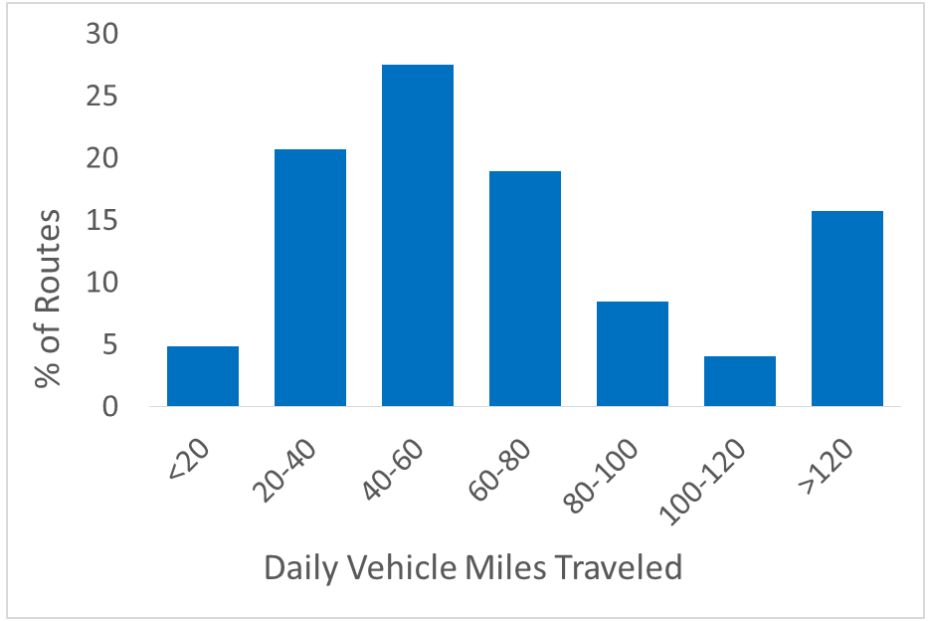
Logos courtesy of PepsiCo, Inc.

Approach

Understanding Customer Requirements

- For class 5-7 pickup & delivery, fleet operators want truck with:
  - comparable performance as conventional and, generally, desire flexibility provided by a range extender
  - capability to operate in pure electric mode for substantial part of route
- Also: require low installation cost of charging infrastructure (EVSE), trucks often stored outside & may not have dedicated EVSE per truck

*combined NREL FleetDNA class 5-7 P & D and Cummins data

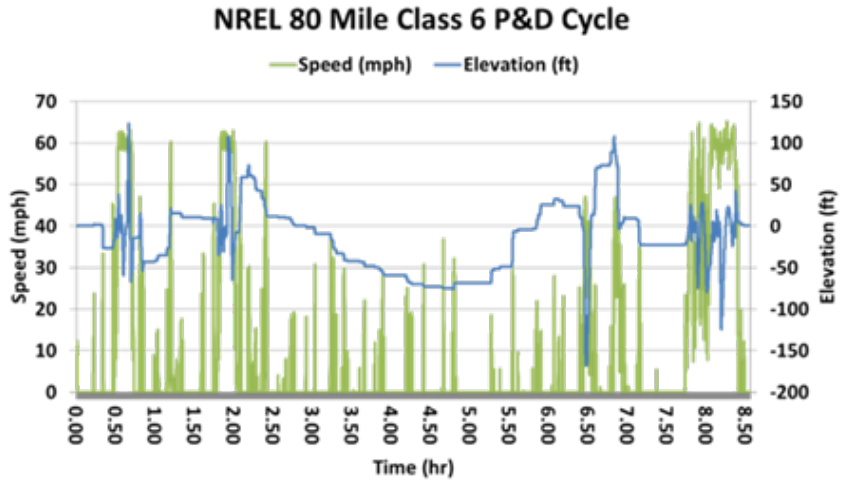


ETREE charging outside at fleet partner distribution center

Approach

Translation into Design Requirements

Fuel consumption reduction	≥ 50-100% on typical class 6 P & D routes
Performance, startability	Equivalent to conventional
Gradeability	Equivalent to conventional for at least 10 minutes
Max vehicle range	≥ 270 miles *(fuel + fully charged battery)*
All electric range (AER)	40 miles
Payload	≥ 6500 lb (snack food)
Truck body	24' box with lift gate

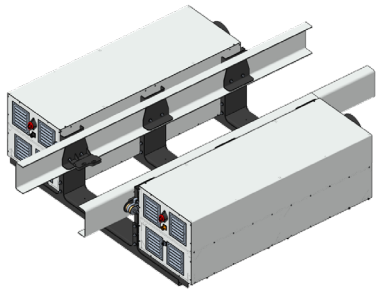


- **NREL 80 mile developed as the ETREE target cycle**; represents 70-80th percentile of required energy of representative drive cycles*
- Secondary target duty cycle developed: NREL 100 mile cycle

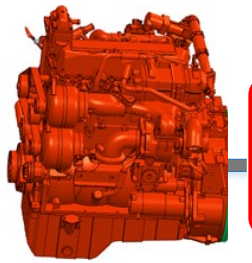
*Duran, A., Li, K., Kresse, J. and Kelly, K. "Development of 80- and 100- Mile Work Day Cycles Representative of Commercial Pickup and Delivery Operation," SAE Technical Paper 2018-01-1192

Approach
Architecture

SOC trajectory management software that maximizing daily use of battery through driver entered and learned parameters is key to architecture approach.



122 kW-h NMC Li-ion battery



155 kW ISB4.5 with DPF, SCR, DOC aftertreatment

damper

130 kW PM generator

~/-

700 V DC bus nominal

-/~

175 kW PM traction motor

Allison 3000 ETREE transmission

Transmission input stop-start system

DPF – diesel particulate filter
SCR – selective catalytic reduction
DOC – diesel oxidation catalyst
NMC – nickel manganese cobalt

Permanent magnet (PM) electric machines with listed continuous ratings

- **J1772 level 2 EVSE** [supports low cost infrastructure]
- **Energy-based range extender control** to ensure optimal usage of grid energy
- **Electrified accessories** [supports electric-only operation]

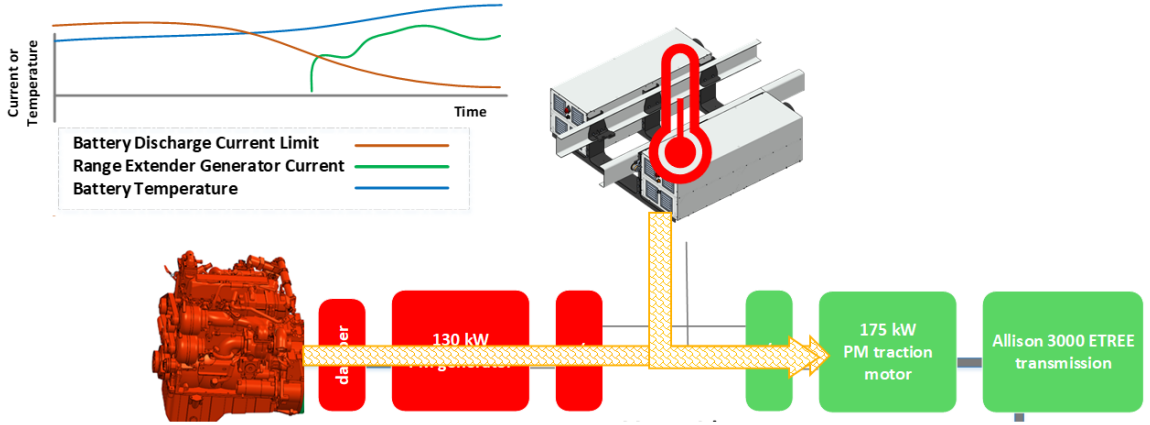
Architecture & ancillary components selected to meet customer requirements on target duty cycle(s)

Approach

Using the range extender to help overcome fleet operator concerns

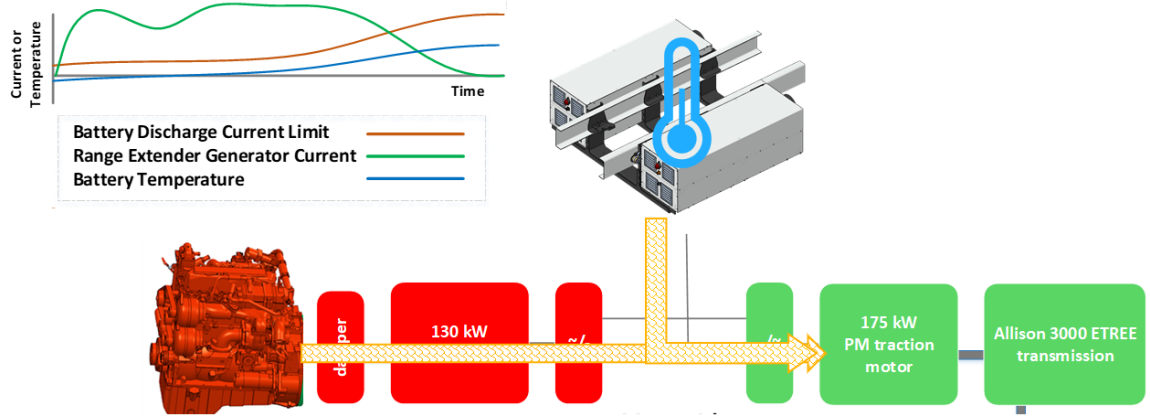
Battery derate due to rising temperature

Use case: as battery cell temperatures increase above nominal operating range or long duration discharge (C) rate exceeded, battery discharge current limit decreases



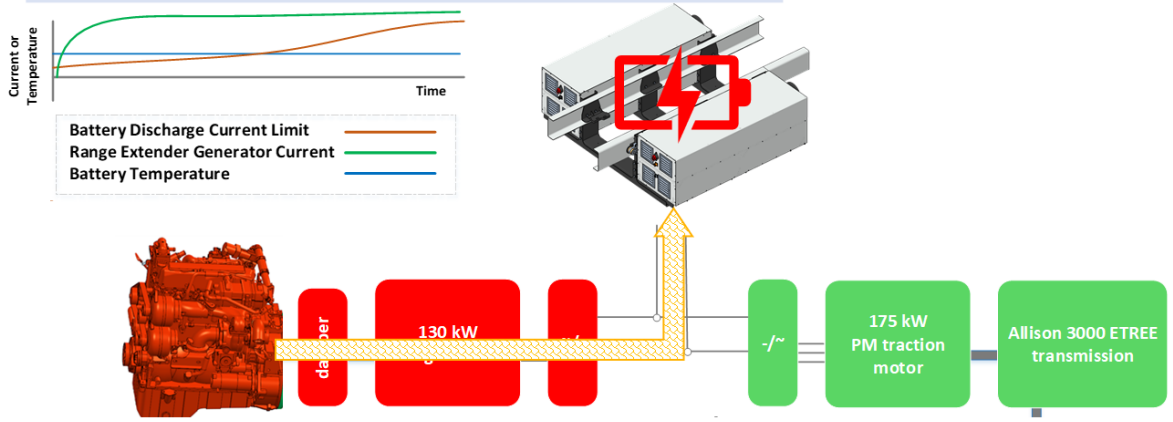
Battery current not available due to cold overnight temperature

Use case: battery current not available due to cold overnight temperatures



Battery state of charge is low and EVSE is not available

Use case: stationary charging when battery state-of-charge low, electric vehicle supply equipment unavailable (e.g., electric grid down, etc.)



Technical Progress

Testing and Development

- Full powertrain demonstrated in test cell
- Completed 2 truck builds
- Completed verification and validation activities for vehicle road worthiness
- Demonstrated 65% fuel reduction over conventional class 6 truck on modified NREL80
- On road testing spanning multiple states and environmental conditions
- Fleet trial with Frito-Lay in Indianapolis ongoing
  - January – August 2020*

*Paused during winter months due to battery hardware communication issue

Columbus, IN to San Antonio, TX
1150 Miles, 3 days

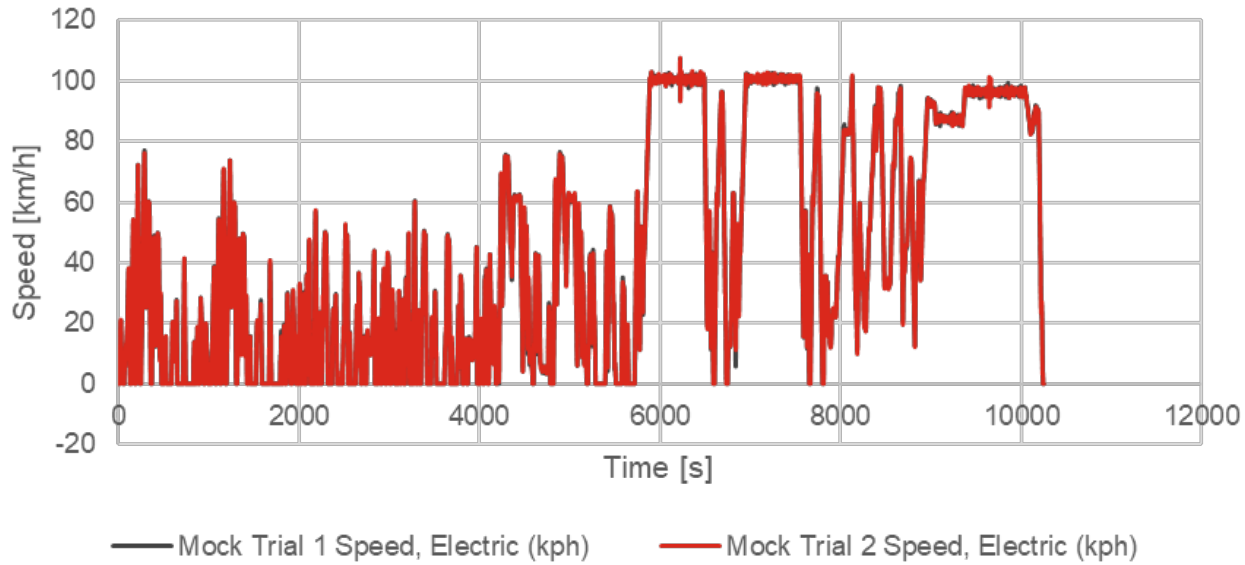
Technical Progress

J1526 Fuel Consumption Testing Complete

- ETREE REEV architecture demonstrated 65.2% fuel reduction on J1526 test over an equivalent baseline class 6 vehicle.
- SWRI semi-autonomous drive system on both vehicles provided consistent NREL80(modified) cycle matching vehicle operation.

**Both vehicles had 4800 lbs. of payload and fuel consumption was measured via gravimetric method.*

Vehicle A Compared to Vehicle B with 95% Confidence Interval	Result		Conf. Int
Average Difference in Fuel Quantity (lbs)	46.46	±	1.27
% Less Fuel Consumed by Veh A	**65.2%**	±	1.8%
Is fuel consumption proven different w/ at least 95% confidence?	**Yes**		



Technical Progress

J1526 Test Cycle vs. Simulation Energy Summary

Uvalde, Test Track: Courtesy of Southwest Research Institute

- Test fuel consumptions for both ETREE and conventional are higher than simulation prediction
  - Possible causes can be inaccurate accessories loss under high ambient temperature
  - Wind speed variation day to day
- However, fuel consumption reduction matches really well
- Test cycle kinetic intensity is higher than the simulation (or target cycle), resulting in 15% more regenerative braking energy recovery
- Test engine efficiency is lower than expected, potential improvement to limit and filter engine power command to higher efficiency zone

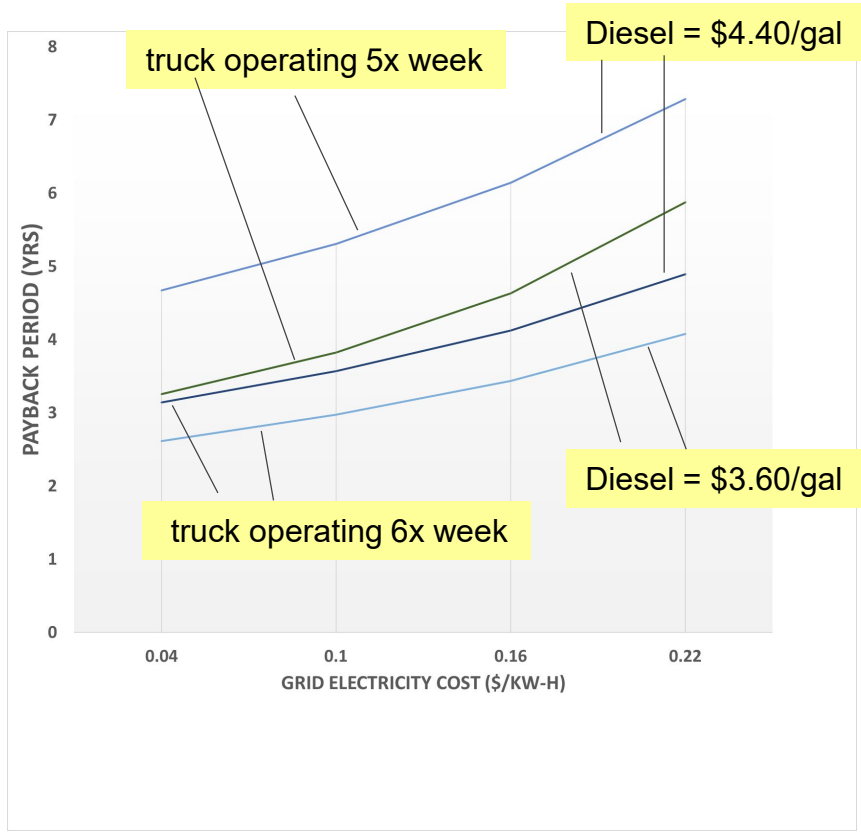
	NREL 80 (sim)	NREL 80 (Test)
Max. Speed (mph)	65	64
Aerodynamic Speed (mph)	50	50
Average Speed (mph)	33	33
Kinetic Intensity (1/km)	0.17	0.26
Mileage Covered	77	77
Vehicle Weight (lb)	25400/21200	25400/21200
SOC Start	97%	97%
SOC End	25%	25%
ETREE Fuel Consumption (lb)	21.5	24.4
Conventional FC (lb)	63	71
FC Reduction (%)	65.8	65.6

Commercial Viability

- To minimize payback period and maximize commercial viability:
  - **maximize battery use** by 1) selecting routes with appropriate distance and energy requirements & 2) operating 6x/week
  - **minimize cost of grid electricity:** use off-peak charging or consistent electric vehicle grid charging cost plan

That [demand charge] is the scary part… the big risk and unknown. It's hard for fleet managers to live in a variable world. The move from diesel to electricity is a learning curve.[1]

- ~3-year payback period is possible:
  - ETREE operating 6x/week
  - daily VMT: 55 - 110 miles
  - grid electricity cost ≤ 14¢/kW-h
- Updates to ETREE for production:
  - Lower cost & smaller range extender
  - Right-sized powertrain components
  - Serial production batteries



(1) PACIFIC GAS AND ELECTRIC COMPANY COMMERCIAL ELECTRIC VEHICLE RATE PROPOSAL PREPARED TESTIMONY, Electric Power Research Institute, *Nov 5, 2018*

Response to Reviewers' Comments from 2019 AMR

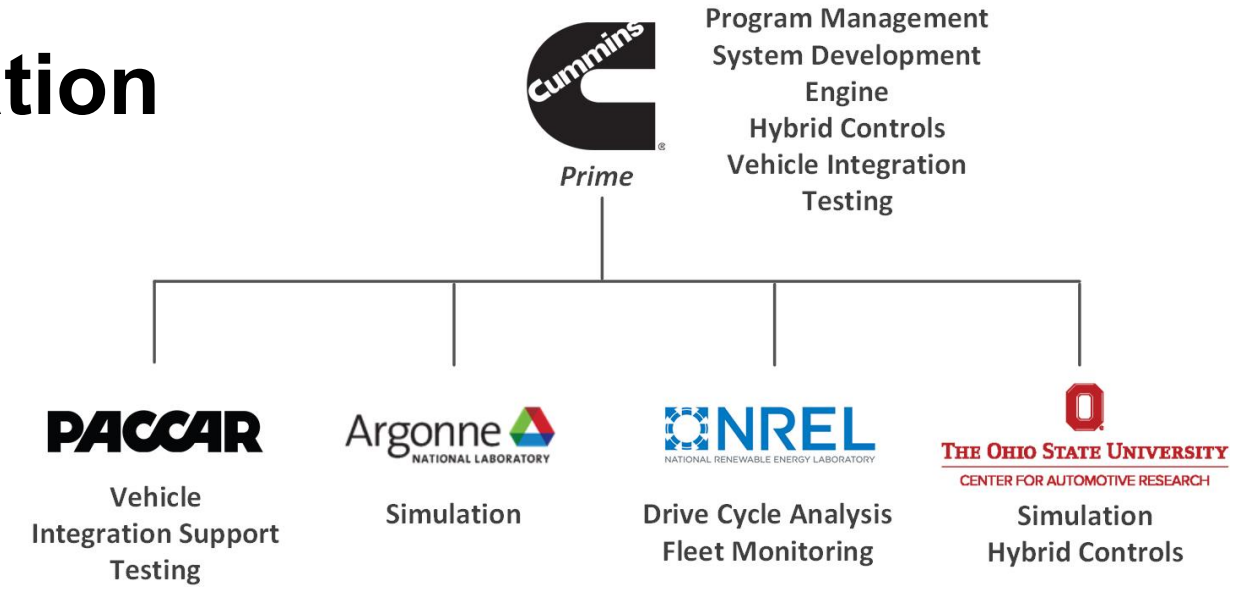
- *"J1526 is a technical challenge that must be overcome" ; "The reviewer said the project is behind schedule and time cannot be made up. Components have been found to be overweight, which affects achievement of the fuel economy goal."*

J1526 testing to demonstrate greater than 50% fuel reduction over a conventional vehicle was a technical challenge. However, based on the team's systematic approach to the architecture, drive cycle development, and testing process we were able to demonstrated 65% fuel reduction over a conventional class 6 truck (slide 14). This was achieved with components that we have highlighted could be optimized for size, weight, and cost, which would further improve the achieved results.

- *"The technical accomplishments score could be higher if more on-road operation (by fleet Partners) was accomplished" ; "However, this reviewer questioned the statistical robustness across the various driving conditions and driver variations given that there are only two vehicles in the project but only one vehicle (Truck 2) will be used in on-road fleet operation by the project partner"*

Our simple energy analysis, simulation, test cell (powertrain) and J1526 testing results were all in agreement; this helps alleviate concern over the results of a small truck fleet. Truck-to-truck variation is important for investigating significance of proposed small fuel economy improvements (<5%), but in large proposed improvements (>50% fuel consumption reduction), it is less of a concern as variation. Additionally, our team has been creative in using the vehicle(s) in a variety of conditions (slide13) to ensure we have vetted key architecture characteristics.

Collaboration



Industry Outreach

- SAE COMVEC Technology Demo at the Indianapolis Motor Speedway Q3 2019
- ETREE lunch and learn industry outreach with Greater Indiana Clean Cities held at Work Truck Show in Q1 2020

Key Suppliers	Allison Transmission - transmission, stop-start system
	WABCO - electronic braking system
	Analytical Engineering, Inc. - vehicle build assistance
	Southwest Research Institute - J1526 testing resources
	Morgan Corporation - van body
	Battery Innovation Center - battery testing

Remaining Challenges and Future Research

- Truck 2: Frito-Lay, Indianapolis (1/15/2020 – 8/30/2020)
  - Complete fleet demo trial period
  - Investigate use of electric-only operation in certain geographic areas (“geo-fencing”)

- Analysis & Future Research
  - Range extender sizing study per class of truck, duty cycles, batteries, geo-fencing requirements, etc.
  - Continued research on state-of-charge management using fleet management data, traffic, weather, etc.
  - Continued industry education and outreach on range extender benefits

Any proposed future work is subject to change based on funding levels

Summary

- Project has developed an electrified powertrain capable of meeting the project objectives
  - Delivers greater than 50% fuel consumption reduction for a wide range of class 6 pickup and delivery drive cycles with substantial EV-only capability
  - Comparable performance to conventional Kenworth K270
  - Developed battery state of charge management controls to optimize system energy use
- Project has demonstrated architecture capability both on road and in fleet use
  - 65% fuel reduction measured over conventional class 6 truck on modified NREL80 cycle in controlled testing
  - Trucks produced have been operated in a variety of environmental conditions(rain, snow, hot, and cold ambient conditions) across multiple states.
  - Truck #2 is currently deployed in fleet service at Frito-Lay distribution center in Indianapolis, IN

Technical Publications

(1) Duran, A., Le, K., Kresse, J. and Kelly, K., "Development of 80- and 100-Mile Work Day Cycles Representative of Commercial Pickup and Delivery Operation", SAE Technical Paper 2018-01-1192, 2018.

(2) Arasu, M., Ahmed, Q. and Rizzoni, G., "Battery discharge strategies for Energy Management in electrified trucks for Pick-Up & Delivery application", ASME 2018 Dynamic Systems and Control Conference, DSCC2018-9116, 2018.

(3) Arasu, M., Ahmed, Q. and Rizzoni, G., "Optimizing Battery Cooling System for a Range Extended Electric Truck", SAE Technical Paper 2019-01-0158, 2019.

(4) Jeffers, M., Miller, E., Kelly, K., Kresse, J., Li, K., Dalton, J., Kadar, M., Frazier, C., "Development and demonstration of a class 6 range-extended electric vehicle for commercial pickup and delivery operation", SAE Technical Paper 2020-01-0848, 2020.

Q+A


Cummins